

# Lyman Break Galaxies at $z \sim 5$ : Rest-Frame UV Spectra<sup>1</sup>

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## ABSTRACT

We report initial results for spectroscopic observations of candidates of Lyman Break Galaxies (LBGs) at  $z \sim 5$  in a region centered on the Hubble Deep Field-North by using the Faint Object Camera and Spectrograph attached to the Subaru Telescope. Eight objects with  $I_C \leq 25.0$  mag, including one AGN, are confirmed to be at  $4.5 < z < 5.2$ . The rest-frame UV spectra of seven LBGs commonly show no or weak Ly $\alpha$  emission line (rest-frame equivalent width of  $0 - 10\text{\AA}$ ) and relatively strong low-ionization interstellar metal absorption lines of Si II  $\lambda 1260$ , O I+Si II  $\lambda 1303$ , and C II  $\lambda 1334$  (mean rest-frame equivalent widths of them are  $-1.2 \sim -5.1\text{\AA}$ ). These properties are significantly different from those of the mean rest-frame UV spectrum of LBGs at  $z \sim 3$ , but are quite similar to those of subgroups of LBGs at  $z \sim 3$  with no or weak Ly $\alpha$  emission. The weakness of Ly $\alpha$  emission and strong low-ionization interstellar metal absorption lines may indicate that these LBGs at  $z \sim 5$  are chemically evolved to some degree and have a dusty environment. Since the fraction of such LBGs at  $z \sim 5$  in our sample is larger than that at  $z \sim 3$ , we may witness some sign of evolution of LBGs from  $z \sim 5$  to  $z \sim 3$ , though the present sample size is very small. It is also possible, however, that the brighter LBGs tend to show no or weak Ly $\alpha$  emission, because our spectroscopic sample is bright (brighter than  $L^*$ ) among LBGs at  $z \sim 5$ . More observations are required to establish spectroscopic nature of LBGs at  $z \sim 5$ .

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## 1. Introduction

In order to understand formation and evolution of galaxies, systematic searches for galaxies in the early universe and detailed studies of the detected galaxies are necessary. In this decade, a number of galaxies detected at high redshift ( $z > 2 \sim 3$ ) has been rapidly increasing. The use of photometric redshift selection from deep broad-band images, especially so-called "Lyman break method" (e.g., Steidel & Hamilton (1992); Steidel, Pettini & Hamilton 1995) gives the largest sample of galaxies at  $z \sim 3$  (Lyman Break Galaxies; LBGs, e.g., Steidel et al. 2003). Extensive studies of them have been revealing individual and statistical nature of star-forming galaxies at  $z \sim 3$  (e.g., Steidel et al. (1999, 1998); Pettini et al. (2001); Papovich, Dickinson, & Ferguson 2001).

At the same time, their optical follow-up spectroscopy has also been made extensively (e.g., Steidel et al. 1996a,b, 1999), and revealed rest-frame UV spectral features of LBGs in addition to their redshift information. Using about 800 spectra of LBGs at  $z \sim 3$ , Shapley et al. (2003) found that about three fourth of them show significant Ly $\alpha$  emission line and the remainders show only Ly $\alpha$  absorption. The LBGs with weaker Ly $\alpha$  emission have stronger low-ionization interstellar metal absorption lines and redder UV continua. These trend suggest that the LBGs at  $z \sim 3$  with weak Ly $\alpha$  emission are more metal enriched and dusty, i.e., chemically evolved than those with strong Ly $\alpha$  emission.

How about properties of LBGs at higher redshift? Are there any signs of evolution of LBGs compared with LBGs at  $z \sim 3$ ? To answer the question and obtain clues to understand formation and evolution of galaxies in the early universe, we made a systematic search for LBGs at  $z \sim 5$  ( $\sim 1$ Gyr earlier to  $z = 3$ ). We carried out wide (effectively  $\sim 600$  arcmin<sup>2</sup>) and deep broad-band ( $V$ ,  $I_C$ , and  $z'$ ) imaging observations toward an area centered on the Hubble Deep Field-North (HDF-N; Williams et al. 1996) with Suprime-Cam (Miyazaki et al. 2002) attached to the Subaru telescope. Thanks to plenty of redshift information of galaxies in and around the HDF-N, we could set suitable color criteria on the two-color ( $V - I_C$  and  $I_C - z'$ ) diagram to effectively select galaxies at  $4.5 \lesssim z \lesssim 5.5$  avoiding foreground contamination, and obtained  $\sim 300$  LBG candidates at  $z \sim 5$  with  $23.5 \text{ mag} < I_C \leq 26.0 \text{ mag}$  (Iwata et al. 2003). This is one of the largest LBG samples at  $z \sim 5$  systematically surveyed. Using this sample, we statistically derived a rest-frame UV luminosity function

(UVLF) of LBGs at  $z \sim 5$ , which shows only a slight change from  $z \sim 5$  to  $z \sim 3$ . We also found that a spatial distribution of LBGs at  $z \sim 5$  shows a large void-like structure and a larger clustering amplitude than that at  $z \sim 3$  (in preparation). The presence of a similar void-like structure is seen in Bremer et al. (2004), and a large clustering amplitude of LBGs at  $z \sim 5$  may also suggest the presence of the larger bias in galaxy formation at  $z \sim 5$  than at  $z \sim 3$  (Ouchi et al. 2004b).

In order to confirm redshifts of the LBG candidates and to study spectral features and relations with other properties of them, we started follow-up optical spectroscopy of our LBG candidates at  $z \sim 5$ . Although similar systematic searches for  $z = 5 \sim 6$  galaxies have been carried out (e.g., Ouchi et al. (2004a); Bouwens et al. (2003); Yan, Windhorst, & Cohen 2003; Stanway, Bunker, & McMahon 2003), a number of spectra of LBGs at  $z \sim 5$  is still extremely small. Moreover most of the spectra obtained so far show only Ly $\alpha$  emission, and the continuum spectral feature and relations with other properties observed in LBGs at  $z \sim 3$  are still quite unknown. In this paper, we present initial results of the optical spectroscopy of a part of our sample. Observations and data reduction are described in section 2, and the results are presented in section 3. In section 4, we compare the results with spectral features obtained for LBGs at  $z \sim 3$ , and discuss possible origins of the similarity and difference seen in spectral features. The magnitude system is based on AB magnitude unless otherwise noted.

## 2. Observations and Data Reduction

We made optical spectroscopy for a subset of our sample using multi-object-spectroscopy (MOS) mode of the Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002) attached to the 8.2-m Subaru Telescope. Main spectroscopic targets are our LBG candidates brighter than  $I_C = 25.0$  mag. Since a mask plate of FOCAS MOS covers a 6' aperture diameter field of view, we designed MOS masks to contain as many main targets as possible on each MOS field. The number of targets thus selected is 17. In addition to them, we selected 7 objects with  $I_C < 25.0$  mag which lie out of the color selection window but near the border line of the window in order to examine our color selection criteria. We also included fainter LBG candidates ( $I_C \geq 25.0$  mag) as many as possible in each mask.

Spectroscopic observations were made on 2003 February 24-26 under clear sky conditions. We used the grism of 300 lines/mm blazed at 7500Å and the SO58 order cut filter. The wavelength coverage was from 5800Å to 10000Å (depending on a slit position on a mask) with a pixel scale of 1.34Å. The slit lengths were typically 10'', and the slit widths were fixed to be 0.''8, giving a spectral resolution of  $R \sim 500$ . One CCD pixel covered 0.''1

and a spatial sampling was  $0.''3 \text{ pixel}^{-1}$  by on-chip three pixel binning. An exposure time of each frame was 0.5 hours, and a total exposure time was 5.5 hours for two masks (mask name F01 and F02), and 5.0 hours for one mask (mask name F08). We nodded the telescope with  $\sim 1''$  along the slit length for each exposure. Spectrophotometric standard stars Feige 34 and Feige 66 were observed with long-slit mode (a slit width of  $2''$ ) for sensitivity correction. Seeing during the observing runs was  $0.''5 - 0.''8$ .

The data were reduced with standard procedure using IRAF<sup>1</sup>. Bias was subtracted by using the overscan region and bias frames, and flat-fielding was made by normalizing averaged dome flat images. The spectra for each target were then carefully aligned and combined for each night. Wavelength calibration was made using night sky emission lines exposed in the object frame with rms errors of  $0.4 - 0.9 \text{ \AA}$ . Sky emission was subtracted by using BACKGROUND task of IRAF. Five pixels were binned for a wavelength direction to improve S/N. One-dimensional spectrum of each object was extracted by using APALL task of IRAF. Since our targets are faint, an aperture for the extraction was determined for each object by eyes to trace the object well. After sensitivity correction (including correction for atmospheric A and B bands by tracing the absorption features in the spectra of the standard stars) was applied to combined spectra for each night, we obtained final spectra by combining them.

### 3. Results

Figure 1 shows spectra of eight objects identified to be at  $z \sim 5$ . Object No.3 (F01-03) has already been identified with an AGN at  $z = 5.186$  by Barger et al. (2002) in a follow-up spectroscopy of 1Ms *Chandra* observation at the HDF-N. A significant continuum break at the redshifted  $\text{Ly}\alpha$  is seen in all the spectra. The average of the depression factor  $D_A$  (Oke & Korycansky 1982) for these objects is  $\sim 0.6$  which is very close to those for QSOs at  $z \sim 5$  (e.g., Songaila & Cowie 2002) and the estimation by Madau (1995). The spectra of seven LBGs (excluding object No.3) also show low ionization interstellar (LIS) metal absorption lines such as Si II  $\lambda 1260$ , O I + Si II  $\lambda 1303$ , and C II  $\lambda 1334$  which are prominent features in UV spectra of nearby starburst galaxies (e.g., Heckman et al. 1998) and in spectra of LBGs at  $z \sim 3$  (e.g., Steidel et al. 1996a; Shapley et al. 2003). Thus they are securely identified to be at  $z \sim 5$ . We determined their redshifts as an average of these

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two or three LIS absorption lines and listed the results in Table 1 as well as their coordinates and photometric data. The obtained redshift range from 4.5 to 5.2 is consistent with that expected from the color selection, Figure 7 of Iwata et al. (2003). We also constructed a composite rest-frame spectrum of the seven LBGs by scaling the continuum level of each spectrum and show the result in Figure 2, together with the composite spectrum of 811 LBGs at  $z \sim 3$  (Shapley et al. 2003).

Intriguingly, spectra of the seven LBGs in Figure 1 show no or weak  $\text{Ly}\alpha$  emission<sup>2</sup>. Four objects show no significant  $\text{Ly}\alpha$  emission line, and the other three objects, No.1, No.6, and No.7 show a  $\text{Ly}\alpha$  emission line, but their rest-frame equivalent widths are rather weak;  $\text{EW}_{\text{rest}} \sim 1\text{\AA}$ ,  $\sim 6\text{\AA}$ , and  $\sim 10\text{\AA}$ , respectively, with an error of 20–30%. The average rest-frame equivalent width of  $\text{Ly}\alpha$  of the seven LBGs is  $2.5\text{\AA}$ , and that derived from the composite spectrum is  $4.5\text{\AA}$ <sup>3</sup>. The position of  $\text{Ly}\alpha$  for some of them locates in the wavelength region of the atmospheric B band absorption. We estimate the uncertainty in the correction for the absorption is at most  $\sim 10\%$ .

A mean rest-frame equivalent width of three LIS absorption lines (Si II  $\lambda 1260$ , O I+Si II  $\lambda 1303$ , and C II  $\lambda 1334$ ) for each of the seven LBGs is measured to be  $-1.2 \sim -5.1\text{\AA}$  and is listed in Table 1. The average rest-frame equivalent widths of Si II  $\lambda 1260$ , O I+Si II  $\lambda 1303$ , and C II  $\lambda 1334$  of the seven LBGs are  $-3.2\text{\AA}$ ,  $-2.3\text{\AA}$ , and  $-2.4\text{\AA}$ , respectively, which agree with those measured in the composite spectrum;  $-2.8\text{\AA}$ ,  $-2.0\text{\AA}$ , and  $-2.4\text{\AA}$ , respectively<sup>4</sup>. Some of the LBGs show a high ionization absorption feature of Si IV  $\lambda\lambda 1393, 1402$  which are also detected in local starburst galaxies and LBGs at  $z \sim 3$ . Most of them lie in the wavelength region where the sky emission is strong or an atmospheric absorption is severe, and we did not measure an equivalent width for each object. The Si IV  $\lambda\lambda 1393, 1402$  feature can be seen in the composite spectrum, thanks to the improvement of the S/N.

Peaks of the  $\text{Ly}\alpha$  emission lines are redshifted with respect to the LIS lines by  $650 \pm 300\text{ km s}^{-1}$ ,  $530 \pm 300\text{ km s}^{-1}$ , and  $700 \pm 300\text{ km s}^{-1}$ , for No.1, No.6, and No.7, respectively. In the composite spectrum, the offset is  $620 \pm 250\text{ km s}^{-1}$ . The value is almost the same as that of the LBGs at  $z \sim 3$  with weak or no  $\text{Ly}\alpha$  emission lines ( $630\text{ km s}^{-1}$  for Group 2 by

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<sup>2</sup>Object No.3 (F01-03) is an AGN and shows a broad ( $\sim 1000\text{ km s}^{-1}$ ) and strong ( $\text{EW}_{\text{rest}} \sim 44\text{\AA}$ )  $\text{Ly}\alpha$  emission.

<sup>3</sup>The S/N of the continuum is improved much in the composite spectrum. This leads to lower the continuum level in a longer wavelength region adjacent to the  $\text{Ly}\alpha$  line, which seem to result in the slightly larger  $\text{Ly}\alpha$  equivalent width for the composite spectrum.

<sup>4</sup>For some objects, the LIS line falls in the wavelength region of the atmospheric A band, and uncertainty of the correction is estimated to be  $\sim 20\%$ .

Shapley et al. (2003)) and also fits a relation between the outflow velocity and the equivalent widths of LIS for LBGs at  $z = 4 - 5$  by Frye, Broadhurst, & Benitez (2002).

We also measured a continuum slope  $\beta$  ( $f_\lambda \propto \lambda^\beta$ ) of the composite spectrum to be  $\beta \sim -0.55$  with a fitting uncertainty of  $\pm 0.3$ . However, since the value is determined in a short wavelength coverage ( $\sim 250\text{\AA}$ ) and depends on an applied binning scale and a clipping threshold in making the composite spectrum, the uncertainty of  $\beta$  would be much larger. Thus we do not discuss the result further.

Among the remainders of the spectroscopic sample in the color selection window with  $I_C < 25.0$  mag, two objects show hints of the presence of a continuum break at the wavelength corresponding to a redshifted Ly $\alpha$  at  $z \sim 5$  and of one or two LIS absorption lines which could be identified to be at  $z \sim 5$ . However, the S/Ns of their spectra are poor and we do not discuss these objects in this paper. For the remaining targets, we could not find any significant features due to the poor S/N. A roughly estimated upper limit on the rest-frame Ly $\alpha$  equivalent width for these objects is  $\sim 20\text{\AA}$ . For the targets with  $I_C \geq 25$  mag, we could not find any significant features due to the poor S/N. The S/N of the spectrum depends not only on the  $I_C$  magnitude, but also on its surface brightness. The objects identified to be at  $z \sim 5$  tend to have the sizes (FWHM) comparable to the seeing size and thus have the brighter peaks than those of the other objects having larger sizes.

Figure 3 shows the positions of the objects identified to be at  $z \sim 5$  (filled circles) in the two color diagram ( $V - I_C$  and  $I_C - z'$ ) as well as the unidentified objects with  $I_C < 25.0$  mag (open triangles). One of the seven LBGs shown in Figure 1 is undetected in  $V$  band ( $V > 28.5$  mag), while the remaining six are detected in  $V$  band within an aperture of  $1.''6$ . Four among seven targets ( $I_C < 25.0$  mag) outside of the selection window are identified to be Galactic M stars (filled pentagons). These results suggest that our selection criteria for objects at  $z \sim 5$  is reasonable.

#### 4. Discussion

Shapley et al. (2003) divided spectroscopically confirmed  $\sim 800$  LBGs at  $z \sim 3$  into four subgroups (each group consists of  $\sim 200$  LBGs) based on rest-frame Ly $\alpha$  equivalent width, and made composite spectra for each group. They found that about three fourth of the  $\sim 800$  LBGs at  $z \sim 3$  show Ly $\alpha$  emission lines, and about two third of them show strong Ly $\alpha$  emission ( $\text{EW}_{\text{rest}} > 10\text{\AA}$ )<sup>5</sup>. They also found that LBGs with weaker Ly $\alpha$  emission have

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<sup>5</sup>Shapley et al. (2003) measured the equivalent width of Ly $\alpha$  line by summing up both emission and

stronger LIS absorption lines, redder UV continuum slopes, and larger  $E(B-V)$  values. The weak Ly $\alpha$  emission, strong LIS absorption lines, the red UV color, and the large  $E(B-V)$  are considered to originate in dusty environment. In the LBGs with no or weak Ly $\alpha$  emission, star formation may occur earlier and may be chemically more evolved than those with strong Ly $\alpha$  emission. Although Shapley et al. (2001) pointed out a possibility that the LBGs with weak Ly $\alpha$  emission are younger than those with strong emission from the SED fitting, this might be reconciled with the chemically evolved nature if the ages derived by SED fitting are affected by the most recent star formation occurred in the LBGs.

The spectra of our seven LBGs (except for one AGN) at  $z \sim 5$  and thus the composite spectrum of them is significantly different from the composite spectrum of LBGs at  $z \sim 3$  as shown in Figure 2. The Ly $\alpha$  emission is much weaker, and the continuum depression in the wavelength region shorter than the redshifted Ly $\alpha$  emission is much larger than those at  $z \sim 3$ . The measured equivalent width of Ly $\alpha$  emission is  $4.5\text{\AA}$  at  $z \sim 5$  while  $15.1\text{\AA}$  at  $z \sim 3$ . The LIS absorption lines are stronger in the spectrum for  $z \sim 5$  than in that for  $z \sim 3$ ; measured equivalent widths of Si II  $\lambda 1260$ , O I+Si II  $\lambda 1303$ , and C II  $\lambda 1334$  are  $-2.8\text{\AA}$ ,  $-2.3\text{\AA}$ , and  $-2.4\text{\AA}$ , respectively for  $z \sim 5$ , while  $-1.7\text{\AA}$ ,  $-2.3\text{\AA}$ , and  $-1.5\text{\AA}$ , respectively for  $z \sim 3$ . However, the spectra of the seven LBGs at  $z \sim 5$  fairly resemble to subpopulations of LBGs at  $z \sim 3$ ; the composite spectra of LBGs at  $z \sim 3$  with no or weak Ly $\alpha$  emission (Group 1 and Group 2 by Shapley et al. 2003) are quite similar to the spectra of our LBGs at  $z \sim 5$ . The average rest-frame equivalent widths of the three LIS absorption lines of the seven LBGs at  $z \sim 5$  is  $-2.8\text{\AA}$  being very close to  $-2.5\text{\AA}$  for Group 1 (no Ly $\alpha$  emission). The average value of  $\text{EW}_{\text{rest}}(\text{LIS})$  corresponds to metallicity of  $12+\log(\text{O}/\text{H}) \sim 8.0$ , if we assume that the relation obtained in the local universe by Heckman et al. (1998) can be applied to the high redshift LBGs, which is not certain at this moment. These results suggest that these LBGs at  $z \sim 5$  are chemically evolved to some degree.

All our LBGs confirmed to be at  $z \sim 5$  show no or weak Ly $\alpha$  emission with relatively strong LIS absorption lines; a fraction of LBGs with strong Ly $\alpha$  emission is very small, though the sample size is still small. We may be witnessing some sign of evolution of LBGs from  $z \sim 5$  to  $z \sim 3$ . The lack of strong Ly $\alpha$  emission as well as the presence of strong LIS absorption at  $z \sim 5$  are likely to be due to their dusty and chemically evolved environment (though the escape of Ly $\alpha$  photons may not be related in a simple way to the metallicity of the galaxy (e.g., Kunth et al. 2003)) and to the presence of more neutral hydrogen in and/or

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absorption. In our case, we measured the equivalent width of Ly $\alpha$  only for the emission part mainly because it is hard to distinguish intrinsic absorption and intergalactic absorption. Thus the value of rest-frame equivalent width of Ly $\alpha$  by Shapley et al. (2003) is the lower limit when it is compared with our equivalent width.

around a galaxy than that at  $z \sim 3$ .

However, it is worth emphasizing that the LBGs we observed are relatively brighter ones among those at  $z \sim 5$  ( $I_C = 25.0$  mag corresponds to  $M^*$  of UVLF at  $z \sim 5$  (Iwata et al. 2003).). There is a possibility that the strength of Ly $\alpha$  emission depends on the magnitude (i.e., UV continuum). Shapley et al. (2003) found for LBGs at  $z \sim 3$  that the average UV magnitude is fainter for the LBGs with stronger Ly $\alpha$  emission. They also found that the average rest-frame equivalent width of the Ly $\alpha$  emission line of faint LBGs is larger than that of bright LBGs among the subgroup with strong Ly $\alpha$  emission of  $EW_{\text{rest}} \geq 20\text{\AA}$ . This trend could also be the case at  $z \sim 5$ . In fact, Lehnert & Bremer (2003), who made a similar search for LBGs at  $z \sim 5$  using  $R$ ,  $I$ , and  $z$  band deep images, found that all of their spectroscopically confirmed six objects to be at  $z \sim 5$  show very strong ( $EW_{\text{rest}} > 30\text{\AA}$ ) Ly $\alpha$  emission lines. The  $I$  magnitudes of them are  $\sim 1$  magnitude fainter than those of our seven LBGs at  $z \sim 5$ . In addition, Ouchi et al. (2003) found that the number density of Ly $\alpha$  emitters (LAEs) at  $z = 4.86$  against to LBGs at  $z \sim 5$  rapidly decreases with increasing UV continuum light ( $i' \lesssim 25$  mag). These observational results suggest that the brighter LBGs tend to show the weaker Ly $\alpha$  emission also at  $z \sim 5$ . It is also worth noting here that the LBGs with secure redshifts tend to show rather compact morphology. Thus the weakness of Ly $\alpha$  emission and the strong LIS absorption lines may also relate to their morphological property, which may also link to an evolutionary stage of galaxies.

If we interpret that the weakness of the Ly $\alpha$  emission is caused by the dusty environment in the LBGs, it might be possible that the brightest LBGs are the most chemically evolved ones at the epoch. It is known that brighter LBGs have a larger correlation length at  $z \sim 3$  (Giavalisco & Dickinson 2001), suggesting that they are associated with more massive dark halos and star formation may occur with biased manner in the earlier epoch as compared with less clustered fainter LBGs. The similar result has been obtained for LBGs at  $z \sim 4$  by Ouchi et al. (2004b). We also found the same clustering segregation with magnitude in our sample of LBGs at  $z \sim 5$  (in preparation). Thus the brighter LBGs at  $z \sim 5$  may be associated with even more massive dark halos and have experienced more biased star formation, resulting in more dusty environment as compared with many of LBGs at  $z \sim 3$  with a strong Ly $\alpha$  emission.

Another possible reason of the difference of Ly $\alpha$  appearance is the effect of a strong clustering of LAEs. Ouchi et al. (2003) and Shimasaku et al. (2003) found that there is an overdensity region ( $\sim 10' \times 10'$ ) of LAEs ( $EW_{\text{rest}} > 14\text{\AA}$ ) at  $z \sim 4.86$  from their wide-field deep narrow-band observations. The observed field ( $44 \text{ arcmin}^2$ ) of Lehnert & Bremer (2003) may happen to fall on an overdensity region of Ly  $\alpha$  emitters; their rest-frame equivalent widths of Ly $\alpha$  emission ( $> 30 - 50\text{\AA}$ ) is larger than the detection threshold of the LAE



selection. While our field of view for the spectroscopy (total of  $\sim 85$  arcmin<sup>2</sup>) may happen to point to a low density region of LAEs and we could not observe LBGs with strong Ly $\alpha$  emission. However, since we selected spectroscopic targets from regions where the surface density of LBG candidates is relatively high, this may be unlikely provided that the distribution of LBGs broadly coincides with that of LAEs at the same epoch.

To summarize, the results presented here may show some sign of evolution in spectroscopic feature from  $z \sim 5$  to  $\sim 3$ , or the presence of luminosity dependence of nature. However, our sample size is too small to reach any significant conclusions. Further spectroscopic observations of LBGs at  $z \sim 5$  over wider field and magnitude range are necessary to reveal spectroscopic nature and discuss relationship with evolution of LBG population.

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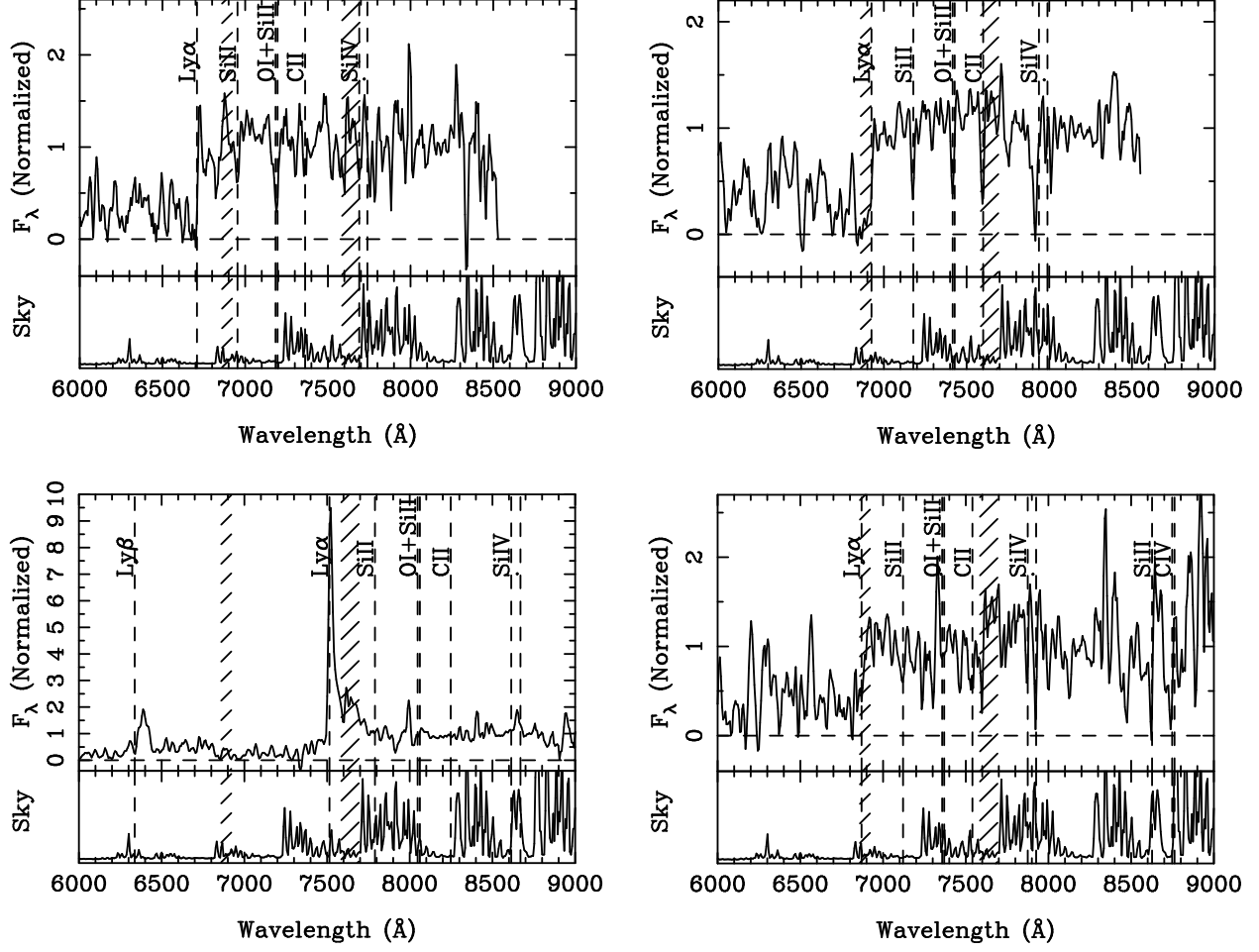


Fig. 1.— Spectra of objects at  $z \sim 5$  with the positions of their rest-frame UV lines. *Top:* Object No.1 (*left*) and No.2 (*right*). *Bottom:* Object No.3 (*left*: AGN of Barger et al. (2002)) and No.4 (*right*). Flux scale is  $F_\lambda$  and normalized with continuum level averaged over the region longer than Ly $\alpha$  excluding sky emission and LBGs absorption lines. These spectra are smoothed with the boxcar over 3-pixel. Sky spectrum is shown in a lower panel of each figure, and atmospheric absorptions are shown as vertical hatched regions.

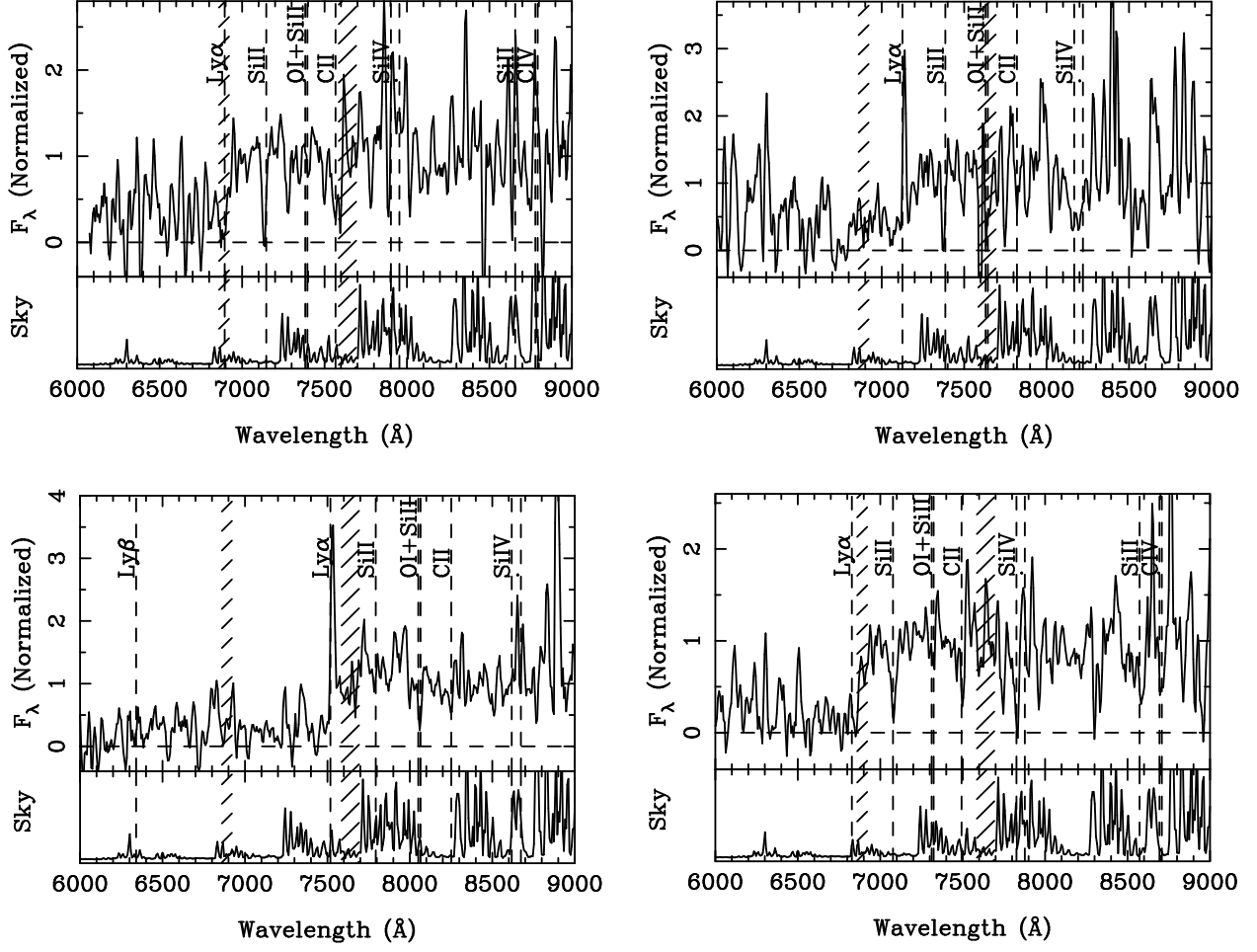


Fig. 1.— Continued. *Top*: Object No.5 (*left*) and No.6 (*right*). *Bottom*: Object No.7 (*left*) and No.8 (*right*).

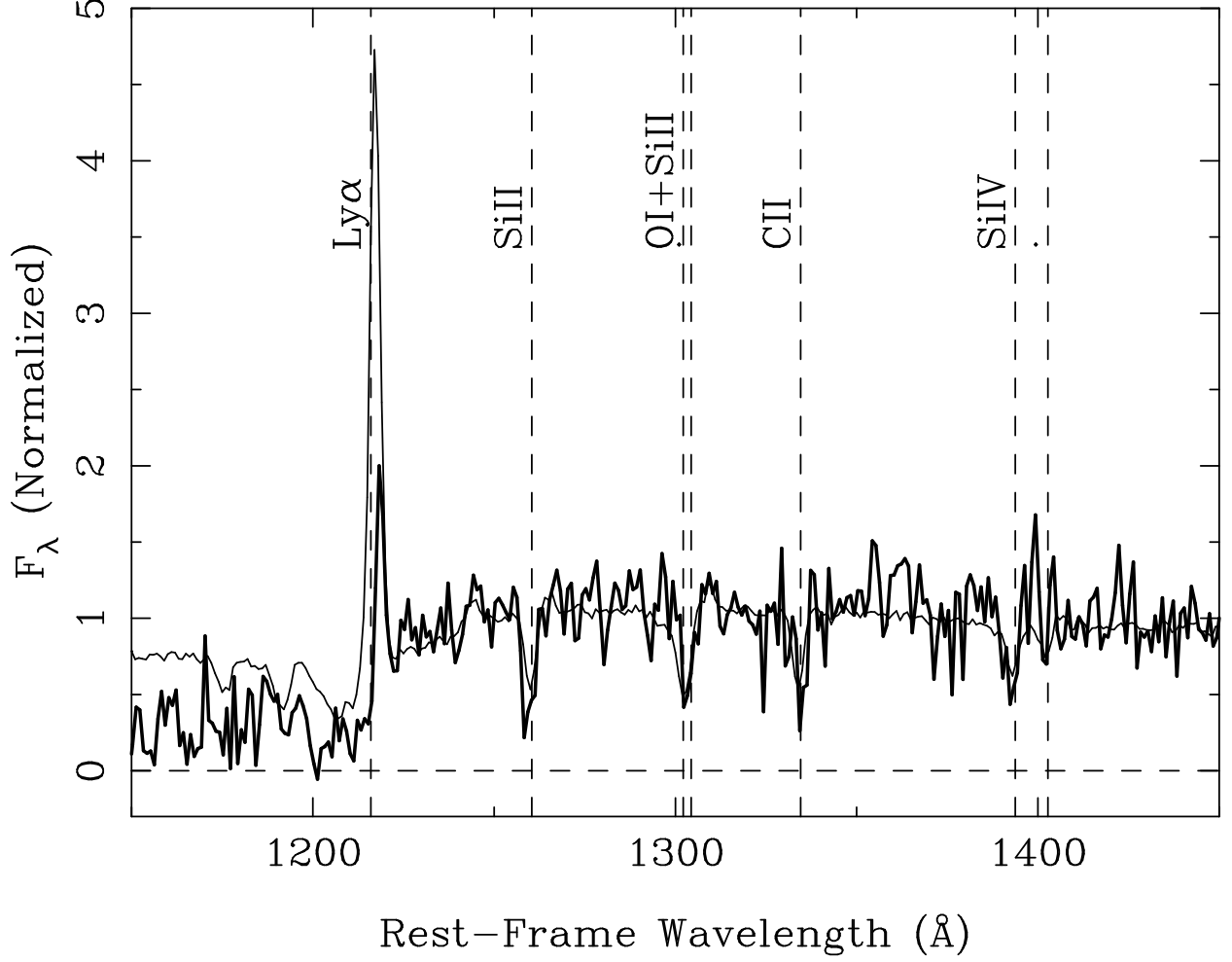


Fig. 2.— Composite spectrum of the seven LBGs at  $z \sim 5$  (thick line). The composite spectrum of 811 LBGs at  $z \sim 3$  by Shapley et al. (2003) is over-plotted (thin line). Both of them are binned to a resolution of  $1\text{\AA}$  per pixel.

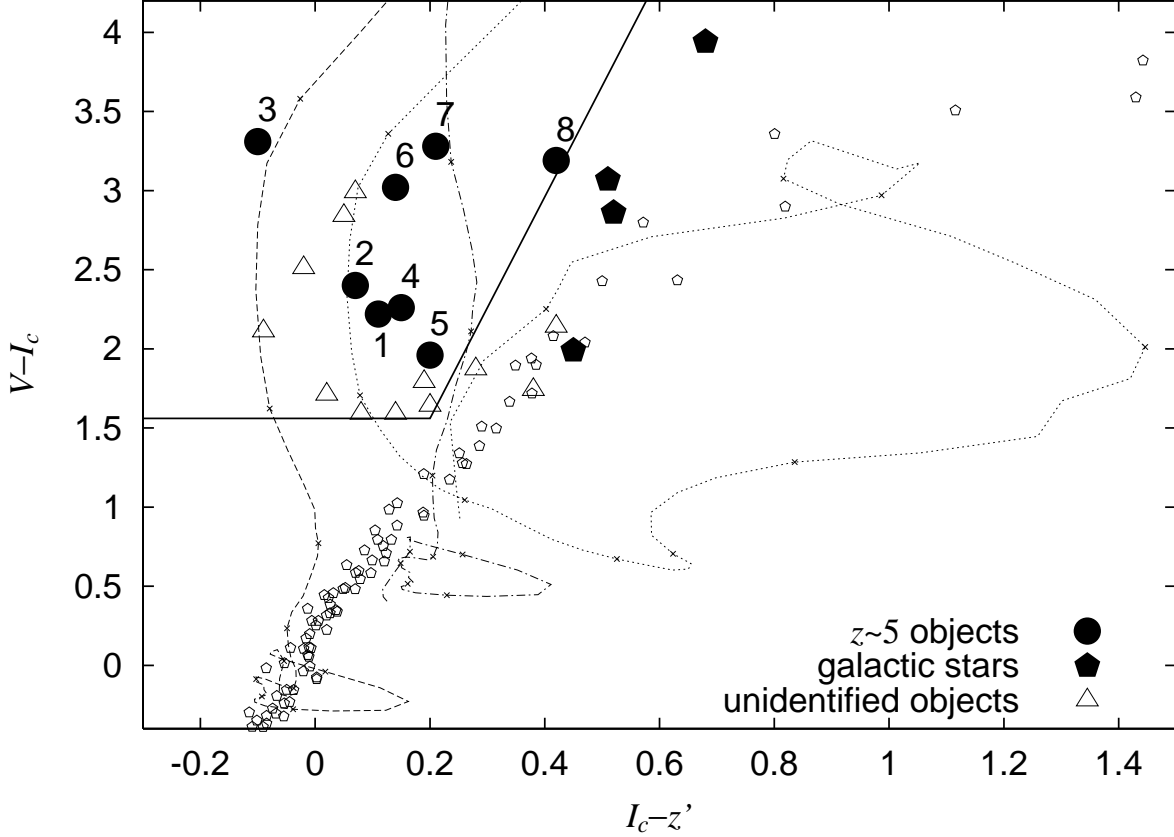


Fig. 3.— Positions of our spectroscopic targets ( $I_C < 25.0$  mag) in two-color diagram. Our color selection criteria for LBGs at  $z \sim 5$ ,  $V - I_C \geq 1.56$  mag and  $V - I_C \geq 7(I_C - z') + 0.16$  mag (Iwata et al. 2003), are indicated by thick lines. Filled circles represent the objects confirmed to be at  $z \sim 5$  with each ID number shown in Table 1. Filled pentagons show objects identified to be Galactic M stars, and open triangles show unidentified objects. A dashed (a dot-dashed) line represents a color track of a model LBG spectrum with the  $E(B - V) = 0.0$  mag ( $E(B - V) = 0.4$  mag) from Iwata et al. (2003). A dotted line refers to a color track of an elliptical galaxy (Coleman, Wu, & Weedman 1980). The small cross symbols are plotted with a redshift interval of 0.5 from  $z = 0$  to  $z = 5$ . No evolution is considered in these models. Small open pentagons indicate the colors of A0 – M9 stars calculated based on the library by Pickles (1998).

Table 1. Spectroscopic sample identified to be at  $z \sim 5$ .

No. (ID)	R.A.(J2000)	Dec.(J2000)	$I_C^a$	$V - I_C^b$	$I_C - z'^b$	Redshift <sup>c</sup>	EW(Ly $\alpha$ ) <sup>d,f</sup>	EW(LIS) <sup>e,f</sup>
1 (F8-2)	12 38 11.2	+62 09 19.3	24.03	2.22	0.11	4.517	1.4	−2.2
2 (F2-2)	12 37 57.5	+62 17 19.2	24.16	2.40	0.07	4.695	0	−2.2
3 <sup>g</sup> (F1-3)	12 36 47.9	+62 09 41.3	24.17	3.31	−0.10	5.186	44.4	−0.7
4 (F1-1)	12 37 05.7	+62 07 43.1	24.62	2.26	0.15	4.650	0	−1.2
5 (F2-6)	12 38 29.0	+62 16 18.8	24.63	1.96	0.20	4.667	0	−5.1
6 (F2-3)	12 38 25.5	+62 18 19.7	24.74	3.02	0.14	4.857	6.3	−2.7
7 (F2-8)	12 38 04.4	+62 14 19.8	24.80	3.28	0.21	5.183	9.8	−2.0
8 (F2-7)	12 38 16.7	+62 18 05.5	24.83	>3.19	0.42	4.615	0	−3.9

<sup>a</sup> $I_C$  magnitude. MAG\_AUTO from SExtractor (Bertin and Arnouts 1996) is adopted. Photometric errors are estimated to be 0.16 mag and 0.19 mag for  $24.0 \text{ mag} < I_C \leq 24.5 \text{ mag}$  and  $24.5 \text{ mag} < I_C \leq 25.0 \text{ mag}$ , respectively.

<sup>b</sup>These values are measured with a  $1''.6$  aperture. The errors in  $V - I_C$  and  $I_C - z'$  colors are  $0.05 - 0.2 \text{ mag}$  and  $0.05 - 0.1 \text{ mag}$ , respectively, depending on the  $I_C$  magnitude and color.

<sup>c</sup>Redshifts determined as an average of the two or three low-ionized interstellar metal absorption lines (Si II  $\lambda 1260$ , O I+Si II  $\lambda 1303$ , and C II  $\lambda 1334$ ) except for the object No.3; we adopted the redshift measured with Ly $\alpha$  emission for this object. The error of redshift is  $\sim 0.006$  (comparable to the spectral resolution).

<sup>d</sup>Rest-frame equivalent width of Ly $\alpha$  emission. A value zero refers to an object without a Ly $\alpha$  emission.

<sup>e</sup>Rest-frame equivalent width of the average of three LIS absorption lines (Si II  $\lambda 1260$ , O I+Si II  $\lambda 1303$ , and C II  $\lambda 1334$ ).

<sup>f</sup>Error of equivalent width for each line is estimated to be  $20 \sim 30\%$ .

<sup>g</sup>X-ray selected AGN (Barger et al. 2002).

Note. — Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.